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PLASMA SPECTROSCOPY OF RUNAWAY ELECTRON PREIONIZED DIFFUSE DISCHARGES[1]

The results of measurement of electrons density (N_e), electron (T_e) and gas (T_g) temperatures and enhanced electric field (E/N) with the optical emission spectroscopy (OES) technique in the plasma of runaway electron preionized diffuse discharge (REP DD) are presented. The measurements were carried out in helium at pressure of 1 – 6 atm and nitrogen at atmospheric pressure at both single pulse and pulse-periodic modes. A single pulse and pulse-periodic modes of REP DD were realized by use of high-voltage pulses with rate of voltage increasing of about $5\cdot10^{14}$ V/s and $2\cdot10^{13}$ V/s, respectively. In the both cases, the gas discharge gaps with sharply nonuniform distribution of electric field strength were used. The values of N_e were obtained with the well-known method based on a measurement of the Stark broadening of atomic spectral lines. Since the state of REP DD plasma is nonequilibrium, the values of T_e and E/N were determined with the method based on the radiation-collisional plasma model. The values of T_g were obtained with the use of a rotational distribution in emission spectrum of nitrogen REP DD plasma.

Keywords: *optical emission spectroscopy, electrons density, electron and gas temperatures, enhanced electric field.*

Introduction

Currently REP DD draws much attention [1–4]. The interest to this subject now is due to the both fundamentals discharge formation's problems and the potential possibility of practical applications of low temperature REP DD plasma. REP DD is characterized by the generation of runaway electron beam and X-ray in gas discharge volume that provides the formation of diffuse discharge at high pressure, very short (fractions – ones ns) duration of discharge formation stage, high level of specific excitation power (up to 1 GW/cm^3). It is explained to impede considerably a study and technical realization of REP DD.

Many published papers devoted to REP DD relate to a runaway electron beam's generation, its time-amplitude characteristics, time behavior and amplitude of a voltage and discharge current pulses. Prospects of these discharges' practical application are associated mainly with the possibility of forming of a low temperature dense plasma at elevated pressure of different gases and their mixtures.

The measurements of above-mentioned parameters of REP DD plasma is important from both fundamental and practical points of view. Firstly, the knowledge of these parameters is important at creation and verification of REP DD's theoretical model. Secondly, it is necessary to characterize the main properties of REP DD's plasma used in practical applications. Early the measurements of N_e in helium and nitrogen and estimation of T_e in nitrogen were carried out by OES technique in [5, 6] and [5], respectively.

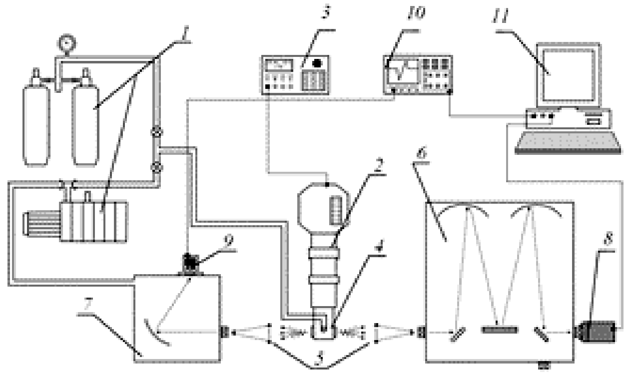

Fig. 1. The block-scheme of experimental setup: *1* – gas pumping system; *2* – pulser RADAN-220 (FPG-60); *3* – generator BNC-565; *4* – discharge chamber; *5* – lens; *6* – monochromator MDR-23; *7* – monochromator VM-502; *8* – CCD-camera PI-MAX 2; *9* – PMT EMI-9781B; *10* – oscilloscope; *11* – PC.

Experimental setup and methods

The block-scheme of experimental setup is shown on the Fig. 1. Single and pulse-periodic modes of REP DD were realized by use of RADAN-220 and FPG-60 pulsers, respectively. The main parameters of them are as follows, respectively: voltage rise time – 0.5 and 3 ns, amplitude on a high resistance load – 250 and 60 kV, voltage pulse duration on a matched load – 2 and 5 ns, pulse repetition rate – 1 and up

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to $2 \cdot 10^3$ Hz. In both cases, REP DD realized at a sharply nonuniform distribution of electric field strength occurred due to a tip (potential electrode) – to plain (grounded electrode) gas discharge gap's geometry. At a pulse periodic mode, a forced gas circulation through the gas discharge gap was realized.

The values of N_e calculated with the use of the Stark broadening of H_α and H_β hydrogen atomic lines [7]. At experimental conditions under study this mechanism of H_α and H_β lines broadening was the main as compare to others ones. At that, the full width at half maximum of the instrument function was about ten time less as compare to values of a Stark broadening of spectral lines. The content of hydrogen admixture in a gas was within the range of 1.5–2.5 %.

The values T_e and E/N of REP DD plasma were determined with the method based on the radiation-collisional plasma model [8, 9]. For T_e and E/N determination according to this model, two conditions are important to fulfil. The first one is an implementation of the Maxwellian type of the electron energy distribution function. The second one – it is necessary that the N_2 ($C^3\Pi_u$) and N_2^+ ($B^2\Sigma_g^+$) radiative states have to be excited by directly electron impact with N_2 molecule in the ground state. At the initial stage of REP DD plasma evolution was shown to satisfy the radiation-collisional plasma model requirements [10]. The values of T_g were calculated with the use of rotational distribution in the emission spectrum of N_2 ($C^3\Pi_u$, v′ = 0) → N_2 ($B^3\Pi_g$, v″ = 0) transition [9]. It is possible due to the high efficiency of the rotational-translational relaxation mechanisms and a fast achievement of an equilibrium between rotational and translational degrees of freedom [11].

Experimental results and discussion

The measurements of N_e values in helium excited in a single pulse mode were made both in time-integrated and time-resolution mode. In the first case, hydrogen lines' profiles were registered by CCD-camera in time-integrated mode. In the second case, a time behavior of hydrogen lines' profiles were registered by photo multiplier tube (PMT) EMI-9781B at profile's scanning in a repetitive pulses mode. Diffuse mode of discharge in helium was observed at pressures up to 15 atm.

The N_e values as a function of helium pressure at the distance of 6 mm from cathode is presented on the Fig. 2. The oscillogram of discharge current and the curve of the N_e time behavior in plasma of REP DD in helium at pressure of 1 atm are shown on the Fig. 3. It is seen, that the maximal N_e value ~ $5.4 \cdot 10^{15}$ cm^{-3} is achieved ~ 5 ns after onset of discharge current. Due to current oscillation the N_e value decreases slowly during about ~ 150 ns and then intensive phase of plasma recombination is observed.

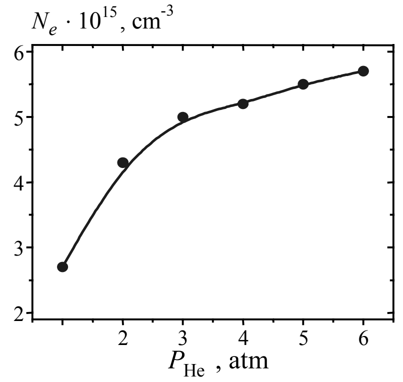

Fig. 2. The dependence of Ne in plasma of REP DD on helium pressure.

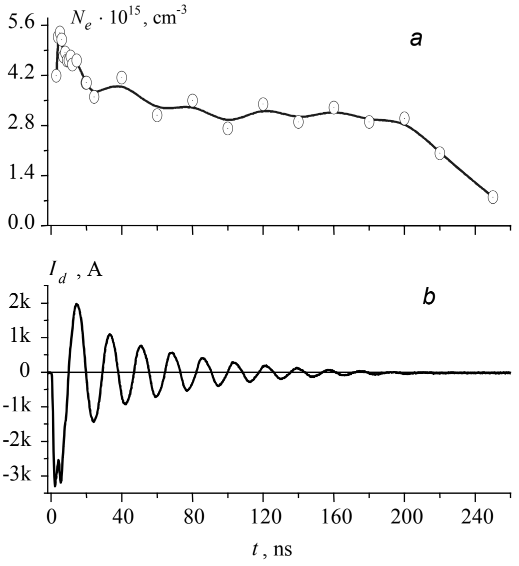

Fig. 3. The time behavior of N_e (*a*), oscilloscope trace of discharge current (*b*). REP DD in helium at pressure of 1 atm.

The parameters of REP DD plasma in a pulse-periodic mode (~ 2 kHz) were determined at nitrogen excitation at pressure of 1 atm. The discharge gap consisted of electrodes with length of ~ 40 cm. The typical photo of glowing of REP DD plasma in nitrogen at pressure of 1 atm is shown on the Fig. 4. The value of N_e in this caseat the time moment of maximum discharge current achievement was ~ $4 \cdot 10^{14}$ cm^{-3}. Time average values of T_e and E/N obtained with using of method based on the determination of ratio $R_{391/394}$ of the peak intensity radiation of the ion N_2^+ (λ = 391.4 nm) and molecule N_2 (λ = 394.3 nm) nitrogen bands were ~ 2 eV and ~ 270 Td, respectively.

As well, dynamics of T_e and E/N values in REP DD plasma of nitrogen at pressure of 1 atm at pulse-periodic excitation was determined. The values of ratio $R_{391/394}$ was found to decrease monotonically during ~ 10 ns of about two times. It means that values of T_e and E/N are reduced by ~ 1.5 times (from 3 to 2 eV for T_e, from 400 to 270 Td for

E/N). It should be noted that, mentioned above time interval ~10 ns is the time interval during which the conditions necessary to apply of the technique are hold, and the results can be considered reliable. After that time interval additional kinetic mechanisms of the N_2 ($C^3\Pi_u$) and N_2^+ ($B^2\Sigma_g^+$) radiative states excitation appear and at formal use of this technique, incorrect values of T_e and *E/N* can be obtained.

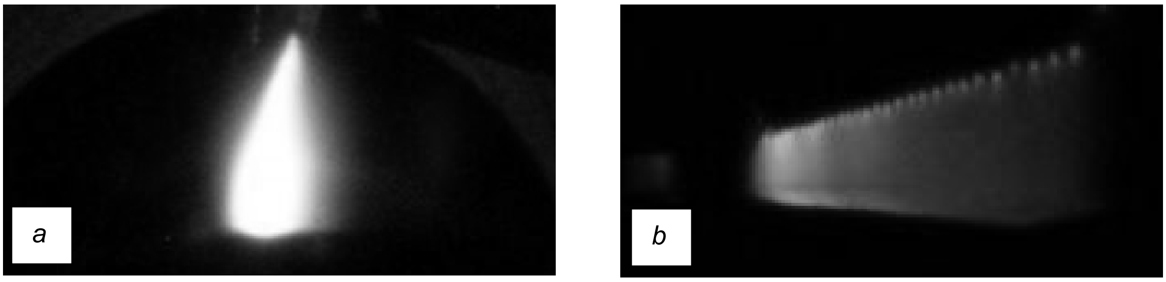

Fig. 4. Front (*a*) and side (*b*) photos of discharge in nitrogen at pressure of 1 atm. Pulse repetition rate is 2 kHz.

To measure the gas temperature T_g in plasma of REP DD in nitrogen the rotational distribution in the emission spectrum of N_2 ($C^3\Pi_u$, v′ = 0) → N_2 ($B^3\Pi g$, v″ = 0) transition was used. A value of T_g it is known to link to a value of rotational temperature T_r due to the relaxation process of inelastic collision between molecules. The relaxation number, which is the average number of inelastic collision required for the exchange of translational and rotational energy, was shown to be of 4–6 [12]. The mean time of N_2 molecules elastic collision can be calculated according to (1):

$$\bar{\tau}_{\mathrm{Coll}} = \frac{1}{[\mathrm{N}_2]\sqrt{2}\cdot\bar{\mathrm{v}}\cdot\sigma}, \tag{1}$$

where $[\mathrm{N}_2]$, $\bar{\mathrm{v}}$, σ – density, thermal velocity and gas-kinetic cross section of N_2 molecules, respectively. Since the value of $\bar{\tau}_{\mathrm{Coll}}$ in atmospheric pressure nitrogen at room temperature is ~ 0.13 ns, the rotational relaxation time is about 0.65 ns. This is more than one order of magnitude shorter than the duration of REP DD under study. The relation of T_g and T_r of the $C^3\Pi_u$ state is as follows [13]:

$$T_g \approx T_r \frac{B_e^0}{B_e^*} \approx 1.09 \cdot T_r, \tag{2}$$

where B_e^0, B_e^* – rotational constants of $X^1\Sigma_g^+$ and $C^3\Pi_u$ states of N_2 molecule, respectively.

The measurements of T_g were carried out at both single pulse and pulse-periodic modes. The typical unresolved rotational emission spectrum of N_2 ($C^3\Pi_u$, v = 0) → ($B^3\Pi_g$, v = 0) transition of atmospheric pressure nitrogen excited by RADAN-220 at single pulse mode is presented on the Fig. 5, *a*. The value of T_g at conditions under study was found to be of ~ 380 K. In the case of pulse-periodic mode, the pulser FPG-60 was used for discharge excitation. The emission spectrum of atmospheric pressure nitrogen plasma on

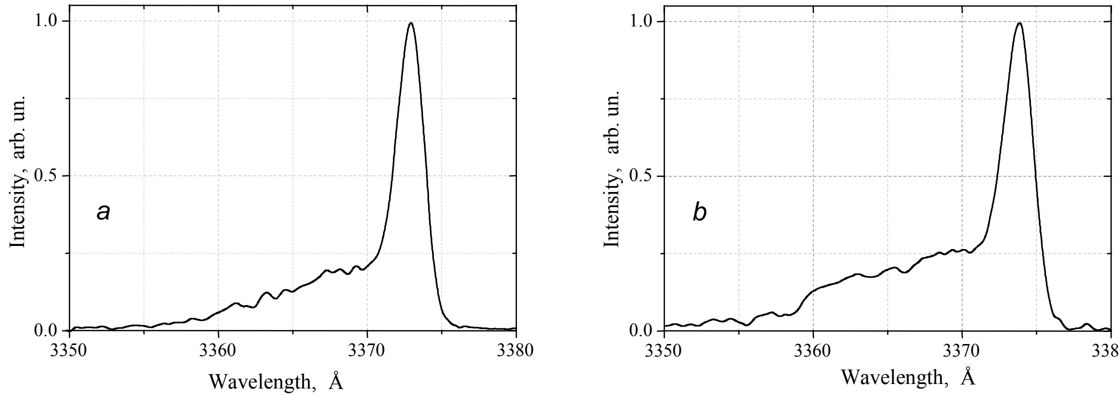

Fig. 5. The spectra of N_2 ($C^3\Pi_u$, v = 0) → ($B^3\Pi_g$, v = 0) transition. Atmospheric pressure nitrogen is excited by RADAN-220 pulser at single pulse mode (*a*) and by FPG-60 pulser at pulse repetition rate of 2 kHz (*b*).

the N_2 ($C^3\Pi_u$ (v = 0) → $B^3\Pi_g$ (v = 0)) transition in this case is presented on the Fig. 5, *b*. The value of T_g calculated was found to be of 820 K.

Conclusions

The main parameters of elevated pressure REP DD plasma in helium and in nitrogen were determined with the OES technique. The maximum N_e value in helium at pressure of 1 atm achieved of ~ $5.4\cdot10^{15}$ cm^{-3}. The plasma of REP DD in nitrogen at pressure of 1 atm and pulse repetition rate of 2 kHz is characterized as follows: $N_e \sim 4\cdot10^{14}$ cm^{-3}, T_e ~2 eV, and E/N ~ 270 Td, T_g ~ 820 K. The dynamics of T_e and E/N values in REP DD plasma of nitrogen was determined, as well.

REFERENCES

1. Babich L.P. // High-Energy Phenomena in Electric Discharges in Dense Gases: Theory, Experiment and Natural Phenomena, ISTS Science and Technology Series. V. 2. – Arlington, Virginia: Futurepast, 2003. – 353 p.
2. Levko D.S., Krasik Y.E., Tarasenko V.F. // International Review of Physics. – 2012. – V. 6. – No. 2. – P. 165–195.
3. Mesyats G.A., Yalandin M.I., Reutova A.G., Sharypov K.A., Shpak V.G., and Shunailov S.A. // Plasma Physics Reports. – 2012. – V. 38. – No. 1. – P. 29–45.
4. Shao T., Tarasenko V.F., Zhang Ch., Burachenko A.G., Rybka D.V., Kostyrya I.D., Lomaev M.I., Baksht E.Kh., and Yan P. // Review of Scientific Instruments. – 2013. – V. 84. – P. 053506.
5. Sorokin D.A., Lomaev M.I., and Krivonogova K.Yu. // News Tomsk Polytechnic Univ. – 2010. – V. 316. – No. 2. – P. 80–85. (in Russian)
6. Yatom S., Stambulchik E., Vekselman V., and Krasik Ya.E. // Physical Review E. – 2013. – V. 88. – P. 013107.
7. Griem H.R. Spectral line broadening by plasmas. – New York and London: Academic Press, 1974. – 408 p.
8. Paris P., Aints M., Laan M., and Valk F. // J. Phys. D: Appl. Phys. – 2004. – V. 37. – P. 1179–1184.
9. Britun N., Gaillard M., Ricard A., Kim Y.M., Kim K.S., and Han J.G. // J. Phys. D: Appl. Phys. – 2007. – V. 40. – P. 1022–1029.
10. Sorokin D.A., Lomaev M.I., Banokina T.I., Tarasenko V.F. Determination of density and temperature of electrons as well as reduced electric field strength in plasma of high-voltage nanosecond discharge in atmospheric pressure nitrogen initiated by runaway electrons // Technical Physics (in press).
11. Ochkin V.N. Spectroscopy of Low Temperature Plasma. – Wiley-VCH, 2009.
12. Phillips D.M. // J. Phys. D: Appl. Phys. – 1975. – V. 8. – P. 507–521.
13. Otorbaev D.K., Ochkin V.N., Rubin P.L. Electron-excited molecules in non-equilibrium plasma. – Moscow: Nauka, 1985.

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